AUTOMATIC TERMINAL GUIDANCE LOGIC FOR RENDEZVOUS VEHICLES

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The ability to complete the rendezvous task automatically is a necessary step in the development of space travel techniques. Many operations can be visualized where it would be necessary to assemble rockets for use as unmanned deep-space probes, or where it would be desirable to assemble the units of a piloted space vehicle for launch from orbit before sending up the manned module. Further, including an automatic system as a back up in manned rendezvous is a desirable safety measure.

The rendezvous task can be divided into several phases. Direct ascent rendezvous, i.e., where the commuter vehicle is launched into orbit and simultaneously performs rendezvous, consists of a launch guidance phase up to burnout of the main stage, mid-course guidance during coast (if there is a coast), terminal guidance which guides the final stage to coincidence with the target station, and docking, where the actual coupling of the vehicles is performed. Alternate modes, such as rendezvous from a parking orbit, may add intermediate phases but in general will retain the portions described above. This presentation will cover the terminal stage of satellite rendezvous for the particular case of "soft" rendezvous, where both position and velocity of the commuter and station are matched.

(Figure 1)

In the past few years quite a number of steering systems for automatic terminal guidance have been proposed and developed with varying degrees of rigor. These can be loosely classified as belonging to two groups; those designed from the fire-control viewpoint, generally of the proportional navigation type, and those designed to work through the orbital mechanics. The sketch at the top of the figure illustrates a proportional navigation intercept, so called because the rate of rotation of the velocity vector of the commuter is controlled in proportion to the angular rate of the line of sight. This scheme is also called constant bearing navigation, since it seeks the condition where the line of sight remains stationary in space. This system is standard in the guidance of interceptors, and was first applied to the satellite rendezvous problem by Dr. Wrigley in 1956 for the "hard" rendezvous case. Hord of Langley Research Center also discussed this system in 1958. Sears and Felleman adapted this system to the "soft" rendezvous task by adding terms to the prescribed thrust to close the velocity difference, and Cicolani of Ames has recently brought out a paper which very thoroughly explores modifications of proportional navigation for various applications. The orbital mechanics approach to terminal guidance was first exploited by Wheelon in 1958 and Clohessy and Wiltshire in 1959. Here the homogeneous equations of motion in a reference frame fixed in the station are solved to determine velocity required to rendezvous. Impulsive corrections are then added to put the commuter on a collision course, and a final impulse added to match velocities. Eggleston of Langley Research Center has brought out a paper which explores application of this technique to mid-course guidance.

The purpose of this presentation is to describe two terminal guidance systems which have been investigated at Langley. While there is a good amount of other work of this nature at Langley, these two systems are presented because they are substantially completely developed analytically and reports on each will be issued shortly. I will discuss the generalized similarities and differences between these two systems, then treat each system in detail, and close by discussing lines of future development which are contemplated.

GENERAL SYSTEM CONSIDERATIONS

The two systems to be described in this talk were investigated by Messrs. Lineberry and Foudriat of Aerospace Mechanics Division, and by myself in the Theoretical Mechanics Division at Langley. Each of these systems is constructed around a vehicle with a single ungimballed thrust unit using attitude control to position the vehicle and therefore the thrust vector in space. In most rendezvous maneuvers a substantial velocity gain will be required in the terminal stage, and weight considerations will preclude more than a single large thrust chamber.

(Figure 2)

Both systems require on-board sensors capable of measuring range, range rate, and slewing rate of the line of sight, in common with almost all such systems. These measurements can be collected by radar, optical or other means.

The two systems differ in that the AMD system belongs to the proportional navigation class while the TMD system can be identified with the orbital mechanics group. Further, the AMD system is based on two engine starts after acquisition, uses an inertial reference, and has been examined for both modulated thrust and on-off operation. The TMD system is a one-start operation using a horizon sensor for its primary reference and currently has been investigated only for modulated thrust control. On-off operation will, of course, require multiple starts.

AMD SYSTEM

(Figure 3)

I will discuss the AMD system first. The principal feature of this system is that it uses a preliminary maneuver to reduce the rendezvous to essentially a one-dimensional problem. The nominal operating sequence is listed on the slide. The inertial reference is established with the X axis colinear with the initial line of sight and the Y and Z axes arbitrarily orthogonal. During the final firing, the thrust vector is tilted differentially from the line of sight to null residual rates of line-of-sight rotation due to instrument and cut-off errors and misalignments using proportional navigation.

(Figure 4)

Both variable and on-off thrust modes have been investigated for this system. Both modes operate based on the one-dimentional rendezvous relation for required acceleration.

$$a_{req} = \frac{\dot{R}^2}{2R}$$

In the variable thrust system, the phase-plane portrait (1) shows the system coasting at constant $\dot{R}$ until some nominal acceleration is reached. The motor fires and the vehicle travels down the constant acceleration path to the origin. Thrust is varied in this period to account for changing mass and system errors. I will discuss path (2) shortly.

The on-off thrust control operation illustrated here shows the vehicle coasting until it reaches the "on" line at a_{req} = 0.25g, then firing with an acceleration of 0.5g to the "off" line where the required acceleration reaches 0.1g. The vehicle "steps" down the band between these lines until rendezvous is achieved. The "g" values used here are typical of cases tested, but not otherwise significant.

So far we have treated only the case where the transverse and line-of-sight relative velocities have been operated on separately. It can be shown that, in gravity-free space, the most efficient rendezvous is performed by initially cancelling all the relative velocity except an infinitesimal component along the line of sight. Path (2) illustrates the case where a large part of the range rate is nulled at the same time as the angular velocity of the L.O.S. is driven to zero. This is more efficient, but lengthens the time to rendezvous considerably. Time to rendezvous can be shortened by increasing the range rate at the first step. It is proposed to add a logical element to the control system which will ascertain the shortest time to rendezvous possible, in the presence of measured initial errors and a prescribed fuel supply, and act to follow the appropriate course.

(Figure 5)

This plot shows measured fuel consumptions for 3 cases using the nominal guidance system and 2 additional cases where a substantial portion of the initial range rate is cancelled. Comparison of these values with the illustrated ideals shows that the control dynamics do not significantly alter the fuel consumption.

Note that the radar must have considerable freedom to bear on the target during the initial correction. If this is undesirable, the direction and firing duration can be pre-computed and radar contact will not be necessary until realignment along the line of sight.

TMD SYSTEM

(Figure 6)

The TMD system strives to approximate the efficiency of thrusting along the velocity vector (gravity turn). The nominal operating mode of this system consists of thrusting principally in the horizontal plane. Near the satellite condition, the commuter velocity lies within one or two degrees of the local horizontal. The velocity direction is not easy to measure directly in space, but the local horizontal provides a readily measurable reference. It has been shown that the gravity turn is very close to the optimum technique of gaining velocity.

The steering system for this scheme is divided into two modes, one for guidance in the vertical plane and one for lateral guidance. The vertical plane steering scheme is based on a closed solution to the equations of motion in space station centered axes where a constant thrust in the horizontal plane is prescribed. This solution contains six parameters subject to manipulation; circumferential displacement and velocity, radial displacement and velocity, thrust and time to rendezvous. Fixing any two parameters yields a unique solution.

In operation, this system is directed toward a nominal aim point. If this point is achieved, the terminal stage fires and the system performs the rendezvous using constant thrust in the horizontal plane. In general, errors will exist and the system will miss the aim point. In this case, the system will generate required thrust, radial velocity and radial displacement based on the measured circumferential relative velocity and displacement and compare the radial commands with measurements. The thrust is then tilted appropriately from the local horizontal to drive these errors to zero, and the path will converge to a condition where thrust in the horizontal plane will complete the rendezvous.

Guidance in the lateral direction is of the proportional navigation type, which here has the advantage of requiring only a rate-of-change of bearing of the L.O.S. in the horizontal plane signal in addition to range and range rates, thus avoiding need for an inertial reference.

(Figure 7)

The steering relations for this system were simplified by elimination of higher-order terms and the resulting equations are listed. No particular difficulty should be experienced in generating these commands The constants C are functions only of the target orbit and the specific impulse of the fuel used. $K_{\dot{\beta}}$ is a predetermined constant.

(Figure 8)

Typical trajectories are shown in this figure for nominal cases and initial circumferential and lateral errors. It should be pointed out that a more sophisticated error control would suppress the oscillations in X. These trajectories are based on a particular case, rendezvous with a station in circular orbit at 400 N.M. using a 200 second nominal burning time.

(Figure 9)

Fuel consumption characteristics for the TMD system are illustrated in this slide for two burning times and the condition mentioned. Investigation has shown that the shortest possible burning time yields the best overall mass ratio, while longer burning times increase the error correction capability of the system. These curves are based on a fixed transfer angle from launch to initiation of the terminal stage of 82.5°, which accounts for the different initial relative velocities.

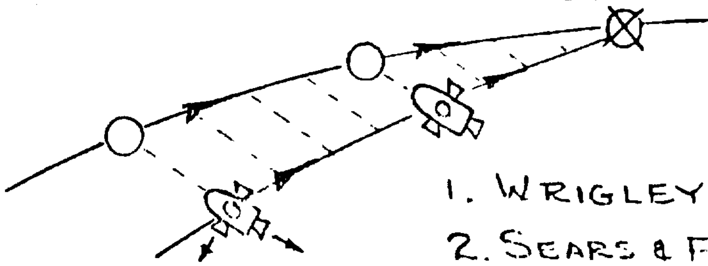
SUMMARY

In summation, it is emphasized that each of these systems has been completely simulated and investigated insofar as is practical in a generalized study. Control dynamics have been considered, and in the AMD system some static instrument and thrust errors have been investigated. Technical notes on each of these systems are in preparation.

The two groups represented by this talk are actively pursuing extensions of this work and corollary topics. Sample lines of current interest include noise effects on various guidance schemes, trajectory optimization, the problems and benefits of handling very large velocity gains in the terminal stage, and more sophisticated automatic logic.

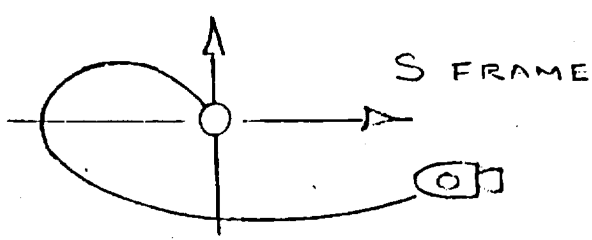
1. Generalized Approaches to Automatic Satellite Rendezvous

I. Proportional Navigation



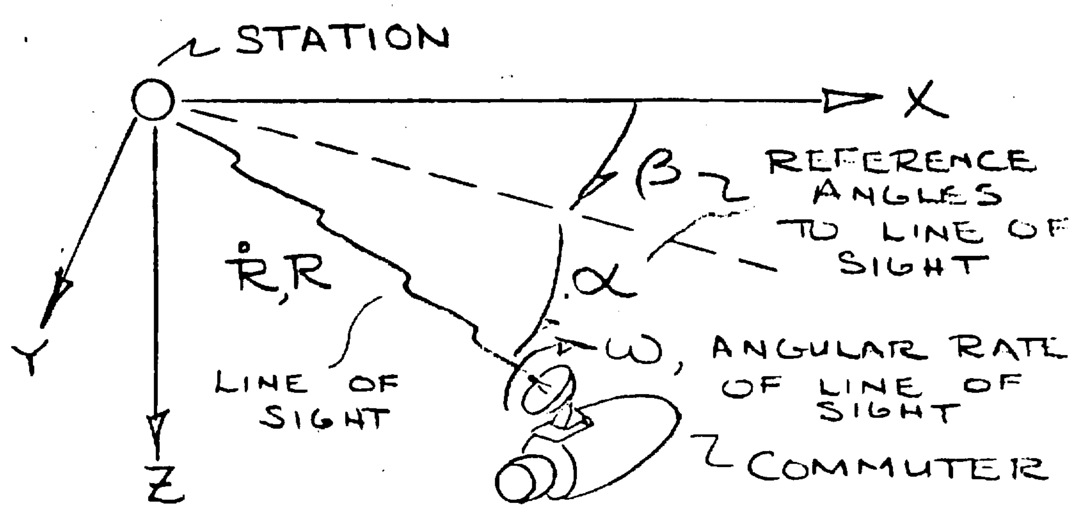
1. Wrigley, 1956
2. Sears & Felleman, 1959
3. Cicolani, 1960

II. Orbital Mechanics

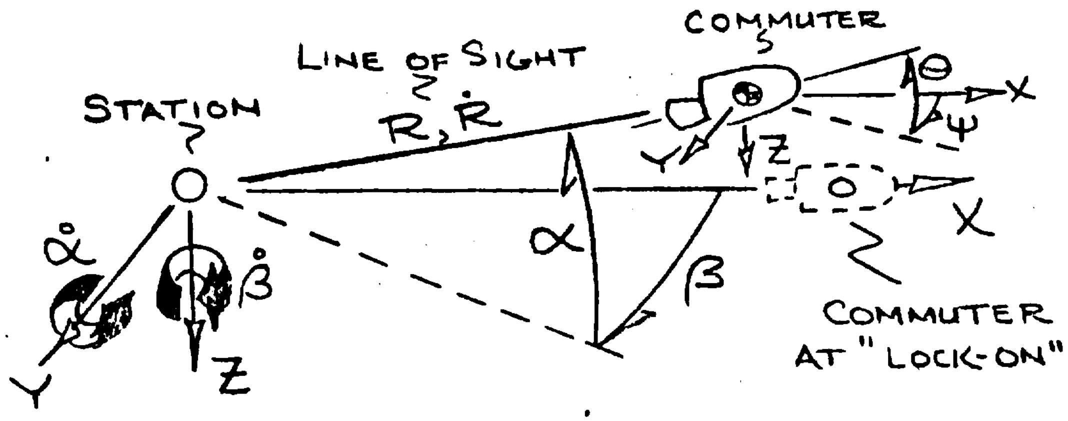


1. Wheelon, 1958
2. Clohessy & Wiltshire, 1959.
3. Eggleston, 1961.

2. Rendezvous Sensor Requirements



3. RENDEZVOUS AXES

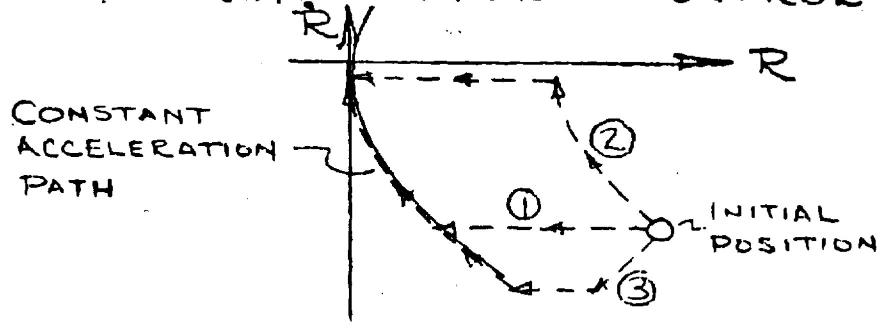


NOMINAL OPERATING SEQUENCE

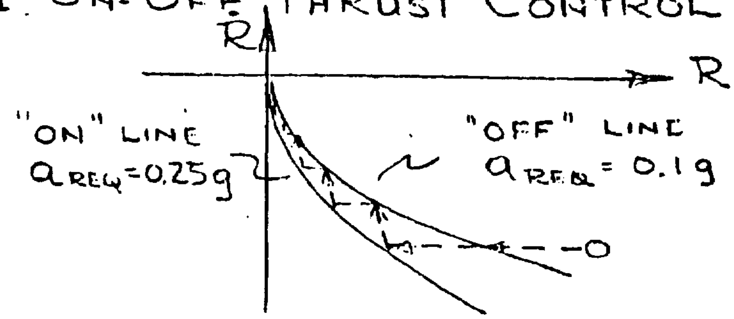
1. SENSOR ACQUIRES STATION, ESTABLISH REFERENCE.
2. VEHICLE ATTITUDE ERECTED WITH THRUST OPPOSING ANGULAR VELOCITY OF L.O.S., FIRE TO NULL TRANSVERSE VELOCITY.
3. VEHICLE REALIGNED TO L.O.S., COMPUTE ACCELERATION REQUIRED TO RENDEZVOUS.
4. COMPUTED ACCELERATION REACHES NOMINAL VALUE, FIRE ROCKET, THRUST UNTIL RENDEZVOUS IS COMPLETED.

RENDEZVOUS IN PHASE PLANE

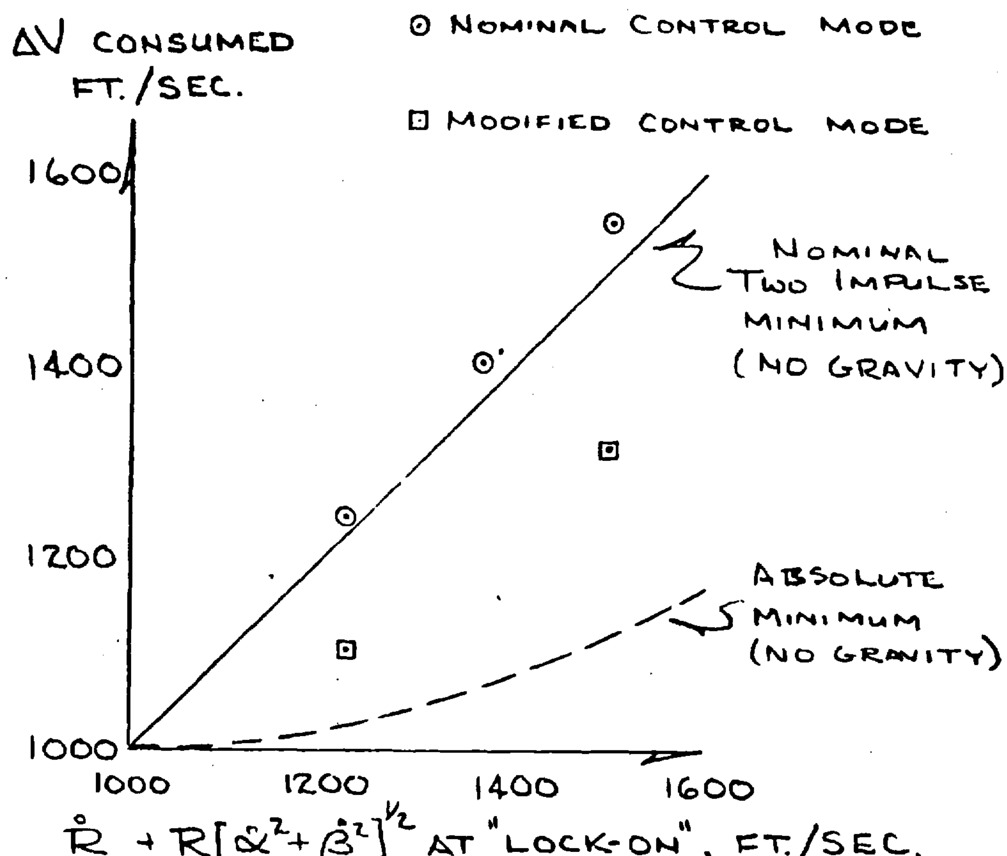
I. VARIABLE THRUST CONTROL

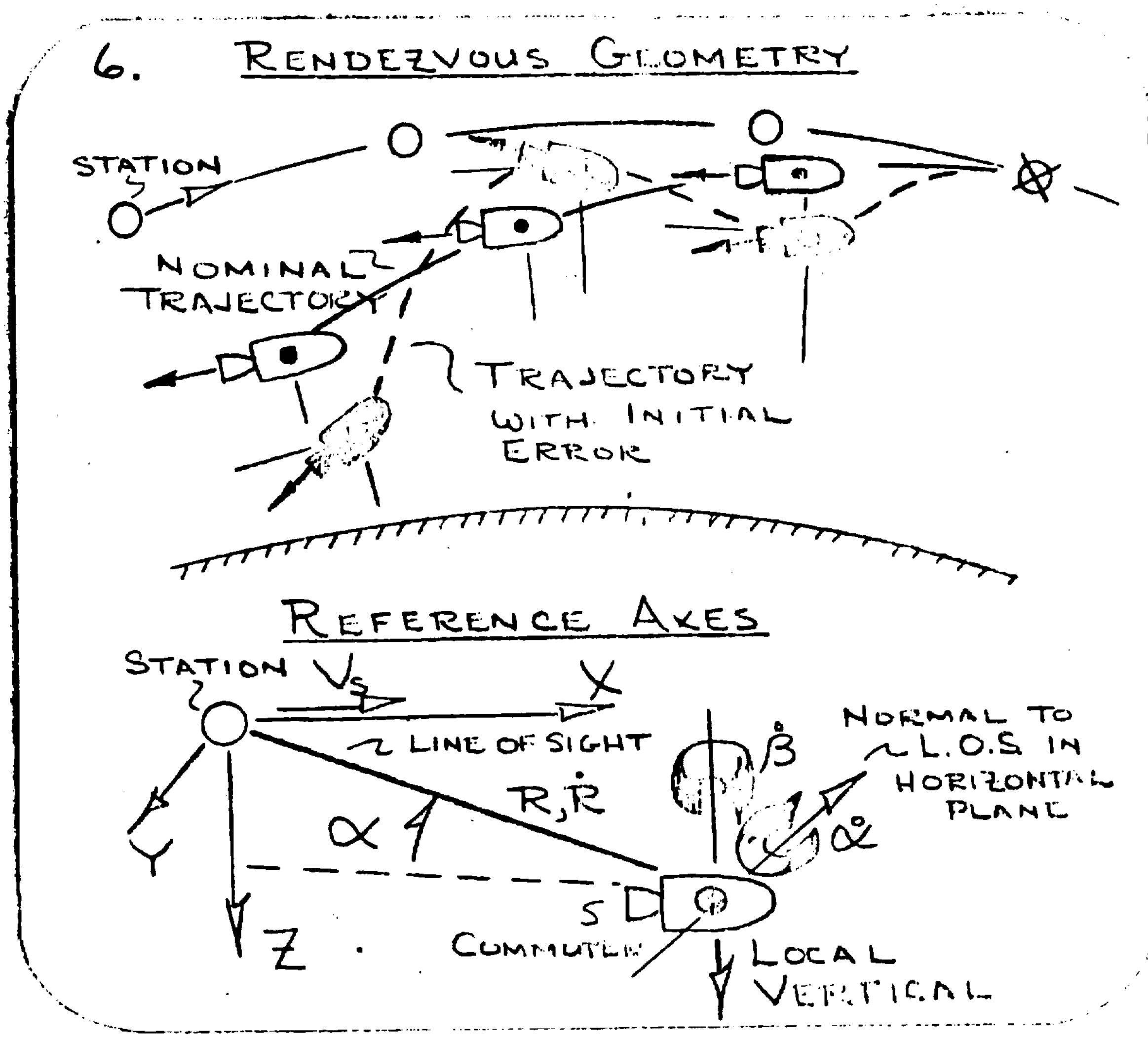


II. ON-OFF THRUST CONTROL



5. RENDEZVOUS FUEL REQUIREMENTS




6. RENDEZVOUS GEOMETRY
STATION
NOMINAL TRAJECTORY
TRAJECTORY WITH INITIAL ERROR
REFERENCE AXES
STATION
V_S
X
LINE OF SIGHT
$R, \dot{R}$
α
$\dot{\beta}$
$\dot{\alpha}$
NORMAL TO L.O.S IN HORIZONTAL PLANE
Y
Z
S
LOCAL VERTICAL

7. RENDEZVOUS STEERING RELATIONS

$$\left(\frac{T}{m}\right)_{com} = \frac{\dot{R}^2}{2R}$$

$$Z_{com} = -R^2\left[\frac{C_1}{R} + C_2\right]$$

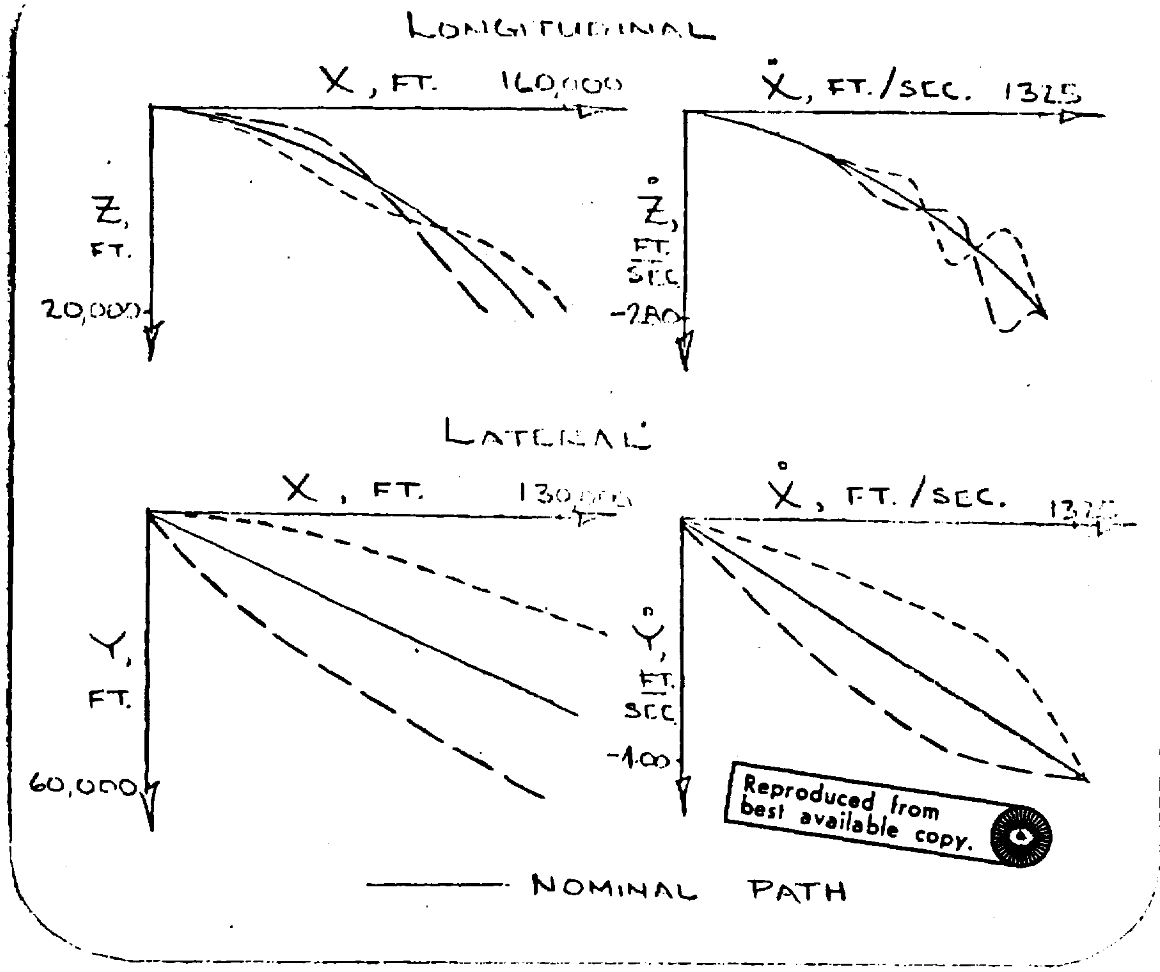
$$\dot{Z}_{com} = -R\left[C_3\dot{R} + C_4\right]$$

$$C_1, C_2, C_3, C_4 = f(R_s, V_s, c)$$

$$\tilde{\varphi} = \frac{K_{\dot{\beta}}\ \dot{\beta}\ \dot{R}}{(T/m)}$$

$\tilde{\varphi}$ = TILT ANGLE OF THRUST FROM L.O.S. IN HORIZONTAL PLANE.

8. RENDEZVOUS GEOMETRY



9. RENDEZVOUS FUEL REQUIREMENTS

——— 200 SEC. TERMINAL STAGE BURNING TIME
$\Delta \dot{X}_0 = 1325$ FT./SEC, $R_S = 400$ N.M.

- - - 400 SEC., $\Delta \dot{X}_0 = 1186$ FT./SEC.